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MATERIALS, PROCESSES AND TESTING LABORATORY
RESIDENTIAL TECHNICAL PROGRESS REPORT:
NOVEMBER, DECEMBER 1980
JANUARY, FEBRUARY 1981

30 January 1982

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ABSTRACT

The U. S. Department of Energy has set a 20-year lifetime goal for terrestrial photovoltaic modules. In its capacity as a Residential Photovoltaic Field Test and Applications Center, Massachusetts Institute of Technology Lincoln Laboratory has established various experimental test sites, ranging in size from 0.1 to 100 kW of peak power, throughout the United States. These sites contain modules from several manufacturers and serve as test beds for photovoltaic system components. This report, the ninth in a series of similar reports,¹⁻⁹ summarizes the activities of the Materials, Processes and Testing Laboratory of the Solar Photovoltaic Field Tests and Application Project during the period of November 1980 through February 1981.

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CONTENTS

	Abstract	iii
	List of Illustrations	vii
	List of Tables	viii
1.0	INTRODUCTION	1
2.0	INTERCONNECT FATIGUE ON BLOCKS II AND III MODEL D MODULES	1
3.0	FIELD TEST/INSPECTION, NBNM	4
	3.1 Location and Replacement of Faulty Modules	5
	3.2 Inspection of Model A Modules	6
	3.3 Curve Tracer Experiments	6
	3.4 Inspection of Model E Modules	6
	3.5 Module Inventory	7
4.0	MODULE FAILURES, MEAD FIELD STATION	8
5.0	MODULE FAILURE ANALYSIS	13
	5.1 University of Texas at Arlington - February and March 1980	14
	5.2 Natural Bridges National Monument - April - June 1980	14
	5.3 Radio Station WBNO - May 1980	16
	5.4 Mead, Nebraska, Agricultural Test Station - June 1980	17
	5.5 MIT LL Rooftop Test Bed - June 1980	18
	5.6 MIT LL Residential Test Facility - August 1980	19
	5.7 University of Texas at Arlington - August 1980	20
	5.8 Rooftop Test Bed - September 1980	20
	5.9 Mead, Nebraska, Agricultural Test Station - 1980	21
	5.10 Natural Bridges National Monument - November 1980	24

CONTENTS (Continued)

6.0	LAPSS OPERATIONAL STATUS REPORT	30
7.0	MODULE DEGRADATION ANALYSIS	31
8.0	FIELD INSPECTION—FLORIDA SOLAR ENERGY CENTER AND THE UNIVERSITY OF TEXAS AT ARLINGTON	36
	REFERENCES	40
	ACKNOWLEDGMENT	40

LIST OF ILLUSTRATIONS

1	Phase 2. Granulation of interconnect.	2
2	Phase 3. Granulation with crease along top of stress relief.	2
3	Phase 3. Granulation with crease midway down stress relief loop.	3
4	Phase 4. Partially broken interconnect with areas of break enhanced.	3
5	Pair of broken interconnects.	4
6	Phase 5. Cracked interconnect showing domes on metal from repeated arcing.	4
7	Phase 5. Crack at bottom of inverted stress relief loop.	4
8	I-V curves for every two adjacent arrays.	5
9	I-V curves for branch circuits 133-7 and -8, NBNM, 11/11/80.	7
10	Model B Block II. Broken interconnect.	21
11	Block II Model D. Impact-cracked cell.	23
12	Block II Model D. Broken interconnects.	23
13	Block II Model D. RTV split and blistered interconnects overheated.	23
14	Block II Model D. Scorch mark on rear side of substrate.	25
15	Block III Model F. Shattered cover glass. Arrow points to burnt area at edge of case.	26
16	Burned area (Fig. 15) where interconnect arced to case.	27
17	Small hole on rear side of module caused by arcing.	28
18	Burned area on foil interconnect by edge of cell.	28
19	Overheated cell caused solder on interconnect to melt. Solder resolidified on cooling.	29
20	Large hole on rear of case under cell. Arrow points to plating on rear of cell.	29
21	LAPSS alignment.	30
22	Recheck of LAPSS on four standard modules after one and two years.	31
23	FSEC branch circuit. 15 Block IV Model E intermediate modules in series.	37
24	FSEC array I-V curve.	37
25	UTA system level curve—dirty.	38

LIST OF ILLUSTRATIONS (Continued)

26	UTA system level curve—clean.	38
27	UTA circuit 8 with failed module.	39
28	UTA circuit 8 after failure replacement.	39

LIST OF TABLES

1	Categorization of Interconnect Fatigue Blocks II and III Model D Modules	2
2	Nebraska Failures — July 1977 to November 1980	9
3	Module Failure at University of Texas at Arlington February, March 1980	15
4	Model C and Model D Failure Analyses, Mount Washington Site,	31
5	Model B, Model F, and Model E Failure Analyses, Mount Washington Site, September 1979—August 1980	34
6	Soil Accumulation Data at UTA, April 1980—February 1981	39

Materials, Processes and Testing Laboratory

Technical Progress Report:

November, December 1980

January, February 1981

1.0 INTRODUCTION

In previous reports, 1-10 41 months of test experience (5/77-10/80) with photovoltaic (PV) modules at various MIT Lincoln Laboratory (MIT LL) experimental PV test facilities were detailed. In this report, further data are presented for the next four-month period (11/80-2/81). Refer to the Table of Contents for the specific details covered in this report.

MIT LL serves as a Field Tests and Applications Center for the U. S. Department of Energy (DOE) to evaluate the energy potential of PV components in various test applications. As part of the DOE/Jet Propulsion Laboratory's (JPL) Large-Scale Procurement Program, MIT LL receives PV modules from various manufacturers for use at its experimental test sites. (The names of the module manufacturers are not relevant to this report, and the module types discussed are referred to as Models A, B, C, D, E, F, and G.) Each module is inspected visually at the factory of origin and a "road map" outlining its physical appearance and workmanship-related anomalies is completed.¹¹

Modules are field tested at two types of experimental test facilities. Modules and the many components of a PV system are evaluated at a Systems Test Facility. Three such sites are discussed in this report: a 25-kWp array field at the Mead Field Station of the University of Nebraska, a 100-kWp array field at Natural Bridges

National Monument (NBNM), and a 7.5-kWp array field at the University of Texas at Arlington (UTA). Modules undergo weathering and soiling in special climates at environmental test sites (urban rooftops in New York City; Cambridge, Massachusetts; Chicago, and a Mount Washington, New Hampshire, weather station). Data from the Mount Washington site is discussed in this report. Data collected at a residential experiment at the Florida Solar Energy Center (FSEC) are also presented.

2.0 INTERCONNECT FATIGUE ON BLOCKS II AND III MODEL D MODULES

Refer to Chapter 4.0 of DOE/ET/20279-117 for a discussion of this problem, which has caused electrical failures in Blocks II and III Model D modules.

An October JPL memo presented criteria to be used to categorize interconnect stress: no damage or pristine; granulation; granulation with a crease; terminated crack; cracked.

In mid-October 1980, an electrical search for failures was made at the Mead, Nebraska, agricultural test site and four Model D Block II modules were removed, as well as an additional eight modules, selected at random, and returned to the Materials, Processes and Testing Laboratory (MP&TL) for analysis. All of the interconnects on the 12 modules were carefully checked at 35X magnification and an inspection road map was

made to categorize the fatigue level of each interconnect (Table I).

Table I
Categorization of Interconnect Fatigue
Blocks II and III Model D Modules

Number	No Damage or Pristine	Granulation (Fig. 1)	Granulation with a Crease (Figs. 2,3)	Terminated Crack (Fig. 4)	Cracked (Figs. 5-7)
Modules	11	12	12	6	3
Inter- connects	57	488	583	16	8

Areas of granulation were found across the top of the stress relief loop and along the bend in the interconnect where it was formed to lie flat on the cell as shown in Fig. 1. Figures 2 and 3 show the condition of granulation with a crease, where the metal becomes more fatigued along the stressed area and the top layer of the metal gradually breaks apart. The terminated crack is shown in Fig. 4; the interconnect has become completely cracked through the thickness of the interconnect on one side, but the crack has not progressed all the way across the width of the interconnect.

Fig. 1. Phase 2. Granulation of interconnect.

Fig. 2. Phase 3. Granulation with crease along top of stress relief.

Fig. 3. Phase 3. Granulation with crease midway down stress relief loop.

As shown in Table I, on three of the modules, eight interconnects were found which had become completely cracked through the thickness, as well as the width, of the metal.

Five of these interconnects were found on one module, two of which occurred in a pair on one cell and caused an open circuit in the cell string (Fig. 5). On one interconnect of the failed pair, domes of metal were found along the cracked area, indicating that repeated arcing had occurred as the interconnect opened and closed during thermal cycling (Fig. 6).

Three other cracked interconnects were found at random on this module.

Fig. 4. Phase 4. Partially broken interconnect with area of break enhanced.

On one of these, the crack had occurred at the bottom of an inverted stress relief loop (Fig. 7).

Two of the terminated cracked interconnects were found on this module also.

On the second module, one redundant pair of cracked interconnects was found to have caused the module to have zero short-circuit current. One of the terminated cracked interconnects was found on this module also.

A pair of redundant interconnects were found to be near failure on the third module. One interconnect was partially cracked while its mate was already completely cracked. Five other partially cracked interconnects were also found on this module.

NOTE

A prior failure report noted

Fig. 5. Pair of broken interconnects.

Fig. 6. Phase 5. Cracked interconnect showing domes on metal from repeated arcing.

that the cause of failure found in a Block II Model B module was due to a work-hardening interconnect which had become cracked. This is the first time that any module, other than the Block II and III Model D modules has been found with this condition. Any future analyses performed on Model B modules will include high magnification examination, mapping of the interconnects and work-hardening categorization.

Fig. 7. Phase 5. Crack at bottom of inverted stress relief loop.

3.0 FIELD TEST/INSPECTION, NBNM

During the week of November 10, 1980, members of the MP&TL visited the NBNM test site to perform various maintenance related activities. These included: generation of I-V curves using a new curve tracer; location and replacement of faulty modules and instruction of NPS people as to how to perform these tasks; inspection of Model A modules for further glass cracking; and completion of the module inventory task.

3.1- Location and Replacement of Faulty Modules

A preliminary analysis of potential problems in the array field was conducted prior to our visit by considering Fig. 8 which illustrates I-V curves for every two adjacent arrays (called a subfield) in the array field. It indicated that there were problems in subfields 110 and 122 for Model F modules, subfield 135 which is the Model F-Model E hybrid and subfield 133 for Model E modules.

Fig. 8. I-V curves for every two adjacent arrays.

Using techniques which are to be described in the NBNM operations and safety manuals, the faulty modules were located and removed. The location and removal processes¹⁰ were illustrated in detail to three people from NPS. A test box, which permits the tracing of a shorted module in an array as well as assisting in the removal process, was demonstrated.

The three Model F failures were shorted to ground. One had three large (almost 2 inches in length by 1/2 inch wide) arc-blasted holes (through the stainless steel substrate) under two cells. On another, a short near the module edge caused the front cover glass to shatter and to provide significant charring on the back. The third shorted module contained a small burn mark on the rear in the center of a cell string away from the edges. The Model E problem was due to a burned out bypass diode which not only shorted the module but also shorted the module frame to ground. Detailed failure analysis information will be presented in a later report.

3.2 Inspection of Model A Modules

On a prior visit in June, it was observed that the cover glass had cracked on 52 of 720 Block II Model A modules. Inspection of all the Model A modules in the array field indicated that no new cracking has occurred since. However, several cracks have grown and traversed from edge to edge. In addition, the PBV (polyvinyl butyrate) adjacent to several cracks has started to yellow. Thus far, no noticeable electrical degradation has occurred.

3.3 Curve Tracer Experiments

A portable curve tracer (developed at MIT-LL) was utilized to generate I-V curves for each of the three types

of modules. The curves for Model E branch circuits 133-7 (normal) and -8 are shown in Fig. 9. As mentioned earlier, there was a module shorted to ground in 133-8 and its presence is indicated by the reduced branch-circuit voltage. There are 15 modules in series in a Model E branch circuit, with a nominal open-circuit voltage of 318 volts or about 21.2 volts per module. Since the open-circuit voltage of the shorted branch circuit was 92.3 volts, the short circuit was located on the fifth module above ground.

Excessive noise was observed to be superimposed on the I-V curves due to the inverters at NBNM coupled with the fact that the current scale utilized was the most sensitive, i.e., 2.5-amperes full scale. The tracer maximum current scale is 40 amperes. The noise was eliminated when the inverters were shut off and the system operated on the diesel generators. The temperature data is missing in Fig. 9 due to problems in the data acquisition system.

3.4 Inspection of Model E Modules

During inspection of Model E modules, it became apparent that several modules had lines of rust coloring which traversed rim-to-rim across several cells. Upon closer examination, several of these rust-colored lines were found to be cracks traversing the cells. An attempt to count the number of modules with one or more of these cells was performed on the lower half of every array frame with Model E modules. Of about 850 modules inspected, 73 were found with one or more suspect cells. If these cells are indeed cracked, diurnal thermal cycling will eventually cause many open-circuited modules. Further developments related to this problem will be continually monitored.

Fig. 9. I-V curves for branch circuits 133-7 and -8, NBNM, 11/11/80.

3.5 Module Inventory

A module inventory was completed in which every module at NBNM was tagged with an MIT LL identification label. Time permitting, a complete listing of all the modules and their locations will be generated.

4.0 MODULE FAILURES, MEAD FIELD STATION

In regard to the number of original and replacement modules fielded at Mead, Nebraska, which had electrically failed as of November 1980, 96 Block II modules, consisting of 61 Model C and 35 Model D modules have been returned to JPL as failures since turn-on in July 1977. Only one of these failures was a replacement module which had been installed on 28 March 1978 and, after 10 months of exposure, was found to have zero short-circuit current due to a cracked cell.

Table 2 is a list of all the modules removed as failures since June 1977. Not all 99 modules were electrical failures. Three of the Model D modules, removed in November 1977, had

exposed interconnects which constituted an electrical hazard to anyone who might inadvertently touch them. The modules were shipped to JPL, along with a PFR for each module, for repair. Three Model C modules were removed as probable electrical failures. It was later determined that the failure was in the external wiring of the modules. Considering that these six modules could not be considered to be electrical failures, the actual number of failures found with reduced or zero short-circuit current is 93 of 2241 or 4.15 percent of the modules.

There have been several causes of module failure at the Mead, Nebraska, field station over the past 39 months: cracked cells, broken junction box wiring, broken interconnects.

In the early stages, a Model C module was found to have a pair of rearside interconnects which had never been soldered to the rear of the cell during the manufacturing process. (This still appears to be a problem with the Model C. Block II and Block

Table 2
Nebraska Failures - July 1977 to November 1980

LL SN	Vendor	Initial Installation	Failure Date	Exposure Time (months)	Failure Mode	Failure Cause
2587	C	7-15-77	10-27-77	3	Zero Isc	Unsoldered rear-side interconnects
3493	C	"	11-17-77	4	"	1 cracked cell
1815	D	"	"	"	"	Exposed inter-connects
1831	"	"	"	"	"	"
1973	"	"	"	"	"	"
2166	"	"	"	"	"	1 cracked cell
2609	C	"	1-31-78	6	"	Module good; wiring defective
2745	"	"	"	"	"	"
3317	"	"	"	"	"	1 cracked cell
2456	"	"	7-20-78	12	"	3 cracked cells
3260	"	"	"	"	"	"
3602	"	"	"	"	"	"
1834	D	"	"	"	"	Unsoldered inter-connects
1965	"	"	"	"	"	6 cracked cells
2064	"	"	"	"	"	3 cracked cells
2144 ¹	"	"	"	7	"	9 cracked cells
2168	"	"	"	12	Intermittent, Isc	2 cracked cells
2169	"	"	"	"	"	9 cracked cells
2444	C	"	9-27-78	14	Reduced Isc	5 cracked cells
1895	D	"	"	"	"	4 cracked cells
1968	"	"	"	"	"	1 cracked cell
3158	"	7-15-77	"	"	"	"
1925 ²	"	3-28-78	1-31-79	10	Zero Isc	"
3052	"	7-15-77	"	18	"	"

Table 2 (Continued)

LL SN	Vendor	Initial Installation	Failure Date	Exposure Time (months)	Failure Mode	Failure Cause
3770	C	7-15-77	3-28-79	20	Reduced Isc	2 cracked cells
4070	"	"	"	"	"	3 cracked cells
4330 ³	D	"	"	"	Zero Isc	Broken wire in junction box
1936	C	"	7-11-79	24	"	4 cracked cells
1946 ⁴	"	"	"	"	"	Module good; defective wiring
2078	"	"	"	"	"	4 cracked cells
2222	"	"	"	"	"	3 cracked cells
2403	"	"	"	"	"	9 cracked cells
2486	"	"	"	"	"	1 cracked cell
2566	"	"	"	"	"	2 cracked cells
2014	D	"	"	"	"	7 cracked cells
2048	"	"	"	"	"	1 cracked cell
3026	"	"	"	"	"	4 cracked cells
3173	"	"	"	"	"	"
3411	"	"	"	"	"	5 cracked cells
4192	"	"	"	"	"	4 cracked cells
1256	C	"	10-24-79	27	Reduced Isc	3 cracked cells
1937	"	"	"	"	"	5 cracked cells
2043	"	"	"	"	"	2 cracked cells
2217	"	"	"	"	"	5 cracked cells
2237 ⁵	"	"	"	"	"	6 cracked cells
2266 ⁶	"	"	"	23	"	1 cracked cell
2358	"	"	"	27	"	4 cracked cells
2397 ⁷	"	"	"	"	"	5 cracked cells
2473	"	"	"	"	"	2 cracked cells
2601	"	"	"	"	"	5 cracked cells
1833	D	"	"	"	Zero Isc	1 cracked cell
2082	C	"	6-11-80	35	Reduced Isc	3 cracked cells

Table 2 (Continued)

LL SN	Vendor	Initial Installation	Failure Date	Exposure Time (months)	Failure Mode	Failure Cause
2212	C	7-15-77	6-11-80	35	Reduced Isc	7 cracked cells
2448	"	"	"	"	"	3 cracked cells
2454	"	"	"	"	Zero Isc	2 cracked cells
2489	"	"	"	"	Reduced Isc	3 cracked cells
3697	"	"	"	"	"	7 cracked cells
3965	"	"	"	"	"	2 cracked cells
1788	D	"	"	"	Zero Isc	Broken inter-connects
1863	"	"	"	"	"	"
1891	"	"	"	"	Reduced Isc	3 cracked cells
1990	"	"	"	"	"	2 cracked cells
2192	"	"	"	"	"	7 cracked cells
2275	"	"	"	"	"	3 cracked cells
2349	"	"	"	"	"	5 cracked cells
2813	"	"	"	"	"	6 cracked cells
2829	"	"	"	"	"	2 cracked cells
3821	"	"	"	"	"	3 cracked cells
4137 ⁸	"	"	"	31	"	"
1807	C	"	10-16-80	39	"	2 cracked cells
2091 ⁹	"	"	"	"	Zero Isc	"
2111 ¹⁰	"	"	"	"	Reduced Isc	6 cracked cells
2319	"	"	"	"	"	3 cracked cells
2395	"	"	"	"	"	4 cracked cells
2416	"	"	"	"	"	2 cracked cells
2441	"	"	"	"	Zero Isc	5 cracked cells
2451	"	"	"	"	Reduced Isc	3 cracked cells
2453	"	"	"	"	"	"
2550	"	"	"	"	"	2 cracked cells
2605 ¹¹	"	"	"	"	"	4 cracked cells
2615	"	"	"	"	Zero Isc	2 cracked cells

Table 2 (Continued)

LL SN	Vendor	Initial Installation	Failure Date	Exposure Time (months)	Failure Mode	Failure Cause
2709	C	7-15-77	10-16-80	39	Reduced Isc	2 cracked cells
2847	"	"	"	"	"	4 cracked cells
2870 ¹²	"	"	"	"	"	2 cracked cells
2906	"	"	"	"	"	"
2968	"	"	"	"	"	"
3095 ¹³	"	"	"	"	"	"
3111 ¹⁴	"	"	"	"	Zero Isc	4 cracked cells
3865 ¹⁵	"	"	"	33	Reduced Isc	5 cracked cells
3896	"	"	"	39	"	4 cracked cells
3911	"	"	"	"	Zero Isc	2 cracked cells
3986	"	"	"	"	Reduced Isc	4 cracked cells
4301 ¹⁶	"	"	"	"	"	1 cracked cell
4039 ¹⁷	"	"	"	33	"	2 cracked cells
4055	"	"	"	39	"	4 cracked cells
1459	D	"	"	"	Zero Isc	"
1463	"	"	"	"	"	Broken inter-connects
1772	"	"	"	"	"	"
1993	"	"	"	"	"	5 cracked cells

1 Removed Sept. 1977 for degradation analysis; reinstalled on degradation frame 2-2-78.

2 Replacement; installed 3-28-78.

3 Repaired at MIT LL; reinstalled and continuing to operate.

4 Not a failure; returned to field.

5 Had reduced short-circuit current per March 1979 inspection.

6 Removed Nov. 1977 for repair; reinstalled on degradation frame 2-2-78.

7 Had reduced short-circuit current per March 1979 inspection.

8 Removed Aug. 1978 for degradation analysis; reinstalled on degradation frame 1-31-79.

9-13, 16 Had reduced short-circuit current per June 1980 inspection.

14 Had reduced short-circuit current per March 1979 inspection.

15, 17 Removed periodically for degradation analysis.

III modules at other sites.) Cracked cells were found on both types of modules after the first four months. On the Model C modules, the cracks were initially found in the area of cells which lay over structural ribs in the substrate. The cracked cells found on a Model D module in November 1977 was believed to be due to the cell going into reverse bias; causing overheating and subsequent cracking.

In May 1978, a five-minute hailstorm, with hailstones as large as three-quarters of an inch in diameter, caused a majority of both types of the modules to have one or more cracked cells. During a July 1978 field inspection trip, nine modules were found to have zero or intermittent short-circuit current. On eight of these modules, this condition was caused by cracked cells. The ninth module (Model D) was found to have a pair of unsoldered topside interconnects. Since the hailstorm, cracked cells have become the prime cause of failure. This is due to the thermal cycling of the modules which causes the cracks to propagate across the cells and eventually cause the modules to have either reduced or zero short-circuit current.

In March 1979, one Model D module was found to have zero short-circuit current. A broken wire in the rearside junction box was found to be the cause of the failure. The module was returned to the MP&TL where it was repaired and returned to the site.

In June 1980, JPL advised MIT LL of a new condition, broken interconnects, which was causing electrical failures in Model D modules. Four modules have been removed from the Mead, Nebraska, site due to this condition.

In addition to the failed modules listed in Table 2, 21 Model D and 27 Model C modules have been removed from the array at various times. These modules were found to have exposed interconnects, protruding cells, exposed ground screws or damaged RTV, all of which constituted a possible electrical hazard. All of these modules were repaired in the MP&TL and then shipped back to the site to be used as spares.

5.0 MODULE FAILURE ANALYSIS

During the period of May through December 1980, visual and electrical failure analyses were performed on 166 modules consisting of 69 Block II Model B, 29 Block III Model F, one Block III Model E, 10 Block III Model D, seven Block III Model C, 35 Block II Model C, and 15 Block II Model D modules.

At the University of Texas at Arlington (UTA) residential test site, 67 (of 240) Block II Model B modules were found to have either reduced or zero short-circuit current. When returned to the MP&TL in July, cracked cells were found to be the cause of failure on 64 of the 67 modules.

In September, two Block II Model B modules were removed from the MIT LL rooftop test bed, where they were found to have zero short-circuit current. Cracked cells and a broken interconnect were ascertained to be the causes of failure.

In the period of April through November, 29 Block III Model F modules were found to be shorted to ground at NBNM. Shorting of the foil interconnect to the stainless steel case was found to be the cause of failure.

In June, one Block III Model E module was found to be open circuited at NBNM. The location of the open cir-

cuit was found, but the cause of failure could not be confirmed.

In May, four Model D Block III modules were returned from the radio station at Bryan, Ohio. Broken interconnects were found to be the cause of failure on two of the modules. The third module was found to have an impact-cracked cell which caused the failure. The failure mechanism for the remaining module was ascertained to be in the array wiring and not in the module.

In June, one Block III Model D module was removed from the MIT LL rooftop where it was found to have zero short-circuit current. A pair of broken interconnects was the cause of the failure.

Five Block III Model D modules were found to have zero short-circuit current at the MIT LL systems test facility (STF) in August. Broken interconnects were the cause of failure on all five modules.

In August, one Block III Model C module was returned from UTA where it was found to have zero short-circuit current. A pair of unsoldered rear-side interconnects was the cause of failure.

Eight Model C modules were found to have either reduced or zero short-circuit current in August at the MIT LL STF. The two Block II modules failed because of cracked cells and the six Block III modules failed because of unsoldered rear-side interconnects.

Seven Block II Model C modules were removed in June from the University of Nebraska at the Mead test site, and an additional 26 were removed in October. The modules were found to have either reduced or zero

short-circuit current. The cause of failure on each of the modules was found to be one or more cracked cells.

In June, eleven Block II Model D modules were found to have either reduced or zero short-circuit current at Mead, Nebraska. An additional four were found in October. Broken interconnects were the cause of failure found for four of the modules. The remaining 11 modules failed because of cracked cells.

NOTE

A failed module is one with a short-circuit current of less than 75 percent of its normal value at the time of measurement.

Many of the modules that had reduced or zero short-circuit current in the field were located on hot days. When tested in the large-area pulsed solar simulator (LAPSS), upon their return to the MP&TL, the modules, at room temperature, would often produce normal curves, depending on the initial cause of failure. One such example is a pair of broken interconnects. As a module's temperature rises, the interconnects expand and move apart, causing the module to become open circuited. As the module cools, the interconnects contract and permit the module to become operational again.

During failure analysis of several of these modules, it was not possible to reproduce the failure mode until the modules were placed in the sun to increase their temperatures.

The following paragraphs categorize module failures together with their respective test sites. The probable causes of failure are specified together with a summary of conditions found in each type of module.

5.1 University of Texas at Arlington - February and March 1980

During the period of February and March 1980, 240 Block II Model B modules were removed from UTA due to a high failure rate. The modules were returned to the MP&TL in July 1980 for electrical testing and failure analysis. These modules had been installed at UTA in November 1978. From that time, until the whole array was replaced with Block III Model C modules in March 1980, 85 failures were found. As 18 of these have been reported on before, table 3 summarizes the causes of failure of the remaining 67 only.

5.2 Natural Bridges National Monument - April - June 1980

During the period of April through June 1980, 32 Block III modules (29 Model F and three Model E) were returned from NBNM. Of these, 26 Model F modules and one Model E module were found to be failures after four to six months of field service.

Two Model E modules were returned to MIT LL because a rear side terminal connection had broken off each module during the array wiring.

Two Model F modules were also returned because of broken rear side terminal studs. A third Model F module was returned because it was found to have an excessive amount of RTV gel leaking out through the edge seals on the rear side of the module.

Paragraphs 5.2.1 and 5.2.2 provide a brief explanation of the results of the failure analysis on both types of modules.

5.2.1 Model E Module Failure-Analysis

One Model E module was found to be open circuited on 26 June 1980, after six months of field service.

When tested in the LAPSS, an I-V curve could not be obtained. When visually examined, no cause for failure could be found. The module was then checked by means of a capacitive open-circuit tester to determine where the open circuit was located. The suspect location was found between two cells. The module was then visually re-examined in that area, using 35X power magnification without success.

The probable cause of failure is attributed to the following: one of the cells may have had a hairline crack across the cell which could not be detected with the microscope; one of the wide metal interconnects may have been unsoldered on the rear side of the cell.

NOTE

After shipment to JPL the module was found to have an unsoldered rear side interconnect in the suspected location.

5.2.2 Model F Module Failure Analysis

The 26 Model F modules were found shorted to ground at various times during the period of mid-April through June 1980.

When flashed in the LAPSS in the usual method, a normal I-V curve was obtained for each module. With the knowledge that the modules had been found shorted to ground, each module was retested in the LAPSS with the positive and negative leads alternately attached to the grounding screw of each module. I-V curves were obtained, on the positive and/or negative connection, for 25 of the 26 modules. This test gave an indication as to which side of the foil interconnect system was shorting to the stainless steel case.

Table 3
Module Failure at University of Texas at Arlington
February, March 1980

Failure Cause	Commentary
Cracked Cells	<p>The primary cause of failure on each of 64 modules was found to be one or more cracked cells.</p> <p>Twenty-three modules were found to have one cracked cell. On five of these modules, the hairline crack could not be followed across the entire cell so as to verify that it was the cause of failure. It is assumed that it was, as the modules failed in the field at elevated temperatures.</p> <p>Seventeen modules were found to have two cracked cells each. On six of these modules, both of the cells had the potential to cause the failure.</p> <p>Fourteen modules were found which contained three cracked cells each. Four of these modules were found on which all three of the cells could cause the cell string to become open circuited.</p> <p>Seven modules were found with four cracked cells on each. On one of these modules, all four cells were cracked in such a way as to cause zero short-circuit current.</p> <p>Three modules were found to have five cracked cells each, and one of these modules had three cracked cells that could cause a failure.</p>
Broken Terminals	<p>The cause of failure on one module was found to be a broken interconnecting terminal strip. The strip was most likely broken when leads were attached to the terminal studs in the rear side junction box and the capturing nut overtightened.</p> <p>One of the 64 cracked cell modules also had a broken terminal strip, but this was not the cause of the failure.</p>
Broken Interconnects	<p>A partially broken interconnect was found on one of the modules with cracked cells.</p>
Unknown	<p>The cause for failure could not be found on two modules. When first tested in the LAPSS, one of the modules produced a highly erratic curve. The module was reflashed and again, an erratic curve was obtained indicating that the module was not functioning properly. The module was visually inspected twice, but no cracked cells were found.</p> <p>When the second module was flashed in the LAPSS, a "shaky" I-V curve was obtained showing the short-circuit current to be reduced to 72% of the normal value. The module was visually examined twice, but a cause for failure was not found.</p>

Table 3 (Continued)

Failure Cause	Commentary
Unknown	These two modules have been installed, along with the remaining 174 good modules from the Texas site, at MIT LL rooftop test bed to be used for various tests. These modules will be monitored for a recurrence of the failure mode.

Upon visual examination of the front of the modules, 24 were noted to have carbon arcing or shorting in the area of the terminals and/or along the periphery of the foil interconnect.

On the rear of one of these modules, the plastic insulator around one of the negative terminals had started to melt and the terminal itself was loose.

Another of the modules had been installed in the field as a replacement for a failed module. As soon as the system was put back on line, the module immediately shorted, causing the cover glass to shatter and the solder to become overheated on a cell adjacent to where the short occurred.*

On 11 of the 24 modules, discoloration from arcing was found on the rear of the metal case as well. Four of these were found to have small to very large holes burned through the pan due to the arcing of the foil interconnect to the case. On one of the four modules, the plastic insulators around the positive terminal studs were partially melted. On a second module, remnants of melted metal and burned RTV were found along the edges of the hole.

* All these modules passed a 1500-vdc leakage test at the factory.

On two modules, no visible evidence could be found to indicate the area of the short. As two sides of the foil interconnect were sandwiched under the frame of the module, it is suspected that the short was occurring in one of these areas.

The failed modules consisted of six different vendor model revisions. Two of each revision were sent to JPL for failure analysis, as well as the two modules on which no cause for failure could be found.

5.3 Radio Station, Bryan, Ohio — May 1980

On 14 May 1980, four Block III Model D modules were found to have either reduced or zero short-circuit current at the radio station in Bryan, Ohio, after nine months of field service.

When tested in the LAPSS, three of the modules produced normal I-V curves. The fourth module produced an I-V curve showing the short-circuit current of the module to be reduced to approximately 50 percent of the normal value.

When one of the three modules with the normal curves was visually examined, no cracked cell or broken interconnects were found. The module was placed in the sun and the short-circuit current was monitored for several days. The module continued to operate at the normal short-circuit current.

It was surmised that the failure mechanism had been in the wiring in the array field rather than in the module. This module will be used as a replacement spare, if needed.

The remaining two modules, which had normal curves, were visually examined and no cracked cells were found. However, several suspect work-hardened interconnects were noted. The modules were then placed in the sun and the short-circuit current was measured and found to be normal. After approximately ten minutes in the sun, both modules were found to have zero short-circuit current.

When the fourth module was visually inspected, an impact-cracked cell was found which could cause the reduction in the short-circuit current and had the potential to cause an open circuit in the cell string. The cause of the impact-cracked cell is unknown. It's possible that the damage occurred either during shipping or installation onto the array frames.

NOTE

During the failure analysis of these modules, the MP&TL was made aware of the problem of work-hardened or broken interconnects that were causing significant numbers of failures at Upper Volta and the Schuchuli Indian Village. Since that time, the interconnects on all Model D modules, whether newly received or returned from the field for failure or degradation analysis, have been carefully examined, at 35X magnification, and any discrepancies have been noted. Refer to DOE/ET/20279-117, Paragraph 4.0, for further information on this problem.

5.4 Mead, Nebraska, Agricultural Test Station - June 1980

Visual and electrical failure analysis was performed on 11 Block II Model D and seven Block II Model C modules. These modules were removed from the Mead, Nebraska, test site on 11 June 1980, where they were found to have either reduced or zero short-circuit current after approximately three years of field service.

Paragraphs 5.4.1 and 5.4.2 provide a summary of the conditions found on each type of module together with their probable cause of failure.

5.4.1 Model C Module Failure Analysis

The seven Model C modules were flashed in the LAPSS and the short-circuit current, open-circuit voltage, and the shape of the I-V curve were noted for each module.

Typically, the short-circuit current for this module is on the order of 0.5 to 0.6 a and the open-circuit voltage is 24.5 to 25.5 volts. One module produced a nearly flat I-V curve showing the short-circuit current to be reduced to 3.4 percent of the normal value.

Visual inspection showed the module to have one cell that was cracked over a structural rib and a second cell that was impact cracked. The impact-cracked cell was the probable cause of failure, as a radial crack, running from the impact area, had cut across the cell (through both main collectors) to the opposite edge of the cell.

The remaining six modules produced I-V curves indicating decreases to 50, 38, (2) 36, and 26 percent, respectively, of the normal short-circuit current.

The seven modules were found to contain a total of 27 cracked cells,

23 of which were impact cracks which were probably caused by a hailstorm in May 1978.

Six of the modules contained only one impact-cracked cell that could cause an open circuit in the cell string. On the remaining module, seven impact-cracked cells were found, two of which had the potential to cause an open-circuit condition.

5.4.2 Model D Module Failure Analysis

When the Model D modules were flashed in the LAPSS, I=V curves were obtained which showed greatly reduced fill factors with somewhat irregular shapes, on 8 of the 11 modules. The short-circuit current for the eight modules was reduced to (2) 92, (2) 84, 76, 53, 38, and 32 percent, respectively, of the normal value.

On another module, an almost flat response curve was obtained showing the short-circuit current to be reduced to 0.1 percent of the normal value.

Upon visual examination of this module, three impact-cracked cells were found. One of these cells had become overheated to a point where the solder on the interconnects had melted and the RTV along the cracked area had blistered. This cell was the probable cause of failure, although any one of the three could have caused the cell string to open circuit, as they all had multiple edge-to-edge cracks traversing the cells.

The nine modules were found to contain 34 cracked cells, 31 of which were impact-type cracks. Thirteen of the 31 impact-cracked cells had the potential to cause an open circuit in the cell string. Three other "normal" cracked cells were found, all of which could also cause an open-circuited condition.

5.5 MIT LL Rooftop Test Bed - June 1980

On 27 June 1980, one Model D Block III module was found to have zero short-circuit current at the MIT LL rooftop test bed after 19 months of exposure.

When tested in the LAPSS, an I-V curve was obtained showing the short-circuit current to be reduced to 81 percent of the normal value. A forward dark curve measurement was made and a normal curve was produced.

When visually examined, no cracked cells were found. However, several interconnects with signs of work hardening were noted, and the pair between cells 19 and 20 appeared to be broken.

Using the forward dark curve as a monitor, pressure was applied in the area over the suspect interconnects and the curve was made to be intermittent.

The module was then placed in the sun and allowed to warm up. After approximately 15 minutes, the short-circuit current was measured and found to be zero. The module was taken indoors and the forward dark curve measurement was immediately repeated. No curve could be obtained at this time. The module was allowed to return to room temperature and the forward dark curve measurement was again repeated. A curve was once again obtained.

Again using the forward dark curve as a monitor, heat was applied (using a heat gun) to the rearside of the module in the area of the interconnects between cells 19 and 20. After approximately five minutes, the interconnects expanded and moved apart, causing the curve to go flat.

These tests verified that these interconnects were broken and had caused the open circuit in the cell string when exposed to elevated temperatures in the field.

NOTE

Many of the interconnects on this module were found to be in the later stages of work hardening, which means that they were partially cracked. This condition has been explained in section 2 of this report.

5.6 MIT LL Residential Test Facility - August 1980

On 7 August 1980, a search for electrical failures was made at the MIT LL residential test facility. Six Block III and two Block II Model C modules and five Block III Model D modules were found to have zero or reduced short-circuit current after 21 months of field service.

The cause of failure found in each type of module is summarized in Paragraphs 5.6.1 and 5.6.2.

5.6.1 Model C Module Failure Analysis

One Block II module was tested in the LAPSS and an I-V curve, showing the short-circuit current to be reduced to 56 percent of the normal value, was obtained.

Upon visual examination, one cell was found which had cracked over a structural rib (rib crack). The crack ran down the center of the cell, cutting through both lateral main collectors. This crack would not cause an open circuit in the cell string, but it could cause a reduction in the operational current of the module.

The second Block II module produced an irregular shaped I-V curve when flashed, but no reduction in the short-circuit current was noted.

This module was also found to have a cell with a rib crack which would explain the irregular shape of the curve.

A forward dark curve measurement was made on both modules and a normal curve was obtained for each module.

When the remaining six Block III modules were flashed in the LAPSS, an irregular shaped I-V curve was produced for one module, while no curves could be obtained for five of the modules.

No cracked cells were found on any of the six modules. However, several suspect areas of unsoldered rearside interconnects were noted.

X-rays were taken of the six modules and they confirmed that there was one pair of redundant interconnects on each module which had not been soldered on the rearside by the manufacturer.

5.6.2 Model D Module Failure Analysis

The five Model D modules were flashed in the LAPSS and a normal I-V curve was obtained for each module. A forward dark curve measurement was made and again, a normal curve resulted for each module.

No cracked cells were found when the modules were visually examined, however, several interconnects were found on each module which showed signs of work hardening. Of these, there was at least one redundant pair of interconnects on each module which appeared to be broken.

Using the forward dark curve as a monitor, pressure was applied in the area of the suspect broken interconnects and the curve was caused to become momentarily flat on each of the five modules.

The modules were then placed in the sun for approximately ten minutes to elevate their temperature, after which time, the short-circuit current of each module was taken and found to be zero.

The modules were taken indoors and the forward dark curve measurement was repeated on the modules while they were still at an elevated temperature. No curve could be obtained for any of the modules at this time.

The modules were allowed to return to room temperature and the forward dark curve measurement was again taken. A normal curve was once again obtained for each module.

These tests confirm that the broken interconnects were the cause of failure on all five modules.

NOTE

In the case of broken interconnects on a Model D module, the failure is generally found when the module is at elevated temperatures in the field. The heat causes the interconnects to expand and open — if they are broken. However, when they are removed from the sun, the interconnects contract as the module cools and the module appears to be working normally again. This explains the normal curves obtained when the modules were initially flashed in the LAPSS and when the first forward dark curve measurements were made.

5.7 University of Texas at Arlington - August 1980

On 22 August 1980, at UTA, one Block III Model C module was found to have zero short-circuit current after five months of field service.

When the module was flashed in the LAPSS, an I-V curve could not be obtained. A forward dark curve measurement was made, and a flat response curve was produced.

When visually examined, one cell was found to have an impact crack along the top edge of the cell. From the impact area, a radial crack ran vertically down the cell, cutting through one of the main collectors, and appeared to terminate near the center of the cell. It is unlikely that this crack would cause the open-circuited condition.

The module was re-examined at 35X magnification to try to locate a pair of possible unsoldered rearside interconnects. Several suspect areas were found.

Using the forward dark curve measurement as a monitor, pressure was applied to each cell in the area of the rearside interconnects. When pressure was applied to the area of the rearside interconnects on one cell, a momentary curve was obtained. It appears that the interconnects on the rear side of this cell were left unsoldered during the manufacturer's assembly process but maintained contact with the rear of the cell until going through five months of thermal cycling in the field.

5.8 Rooftop Test Bed - September 1980

On 29 September 1980, during the reconfiguration of the test bed array at MIT LL, two Model B Block II modules were found to have zero short-circuit current.

When tested in the LAPSS, one module produced an I-V curve showing the short-circuit current to be reduced to 89 percent of the normal value.

The module was visually examined and found to have one cell which had a crack running into the center of the cell from the right side, cutting through one of the main collectors — then down the cell — exiting at the left side of the rearside interconnect. This crack could cause an open circuit in the cell string.

A broken interconnect was also found between two cells. Since redundant interconnects were not utilized in the design of this module, the one broken interconnect would cause the zero short-circuit condition (Fig. 10).

Fig. 10. Model B Block II. Broken interconnect.

One other interconnect was also found on this module which had started to crack across the top.

After visual inspection, a forward dark curve measurement was made and no curve could be obtained. This indicated that the cell string had become open circuited since the module was flashed in the LAPSS.

When the second module was flashed in the LAPSS, no I-V curve was obtained.

When visually examined, three cracked cells were found. Two of the cells had edge-to-edge diagonal cracks cutting through the main collectors. The third cell had cracked in a Y shape with the arms of the Y straddling the interconnect, then joining with the tail, which ran down the cell, and exited to one side of the rear side interconnect. All three of the cells have the potential to cause an open circuit in the cell string.

A forward dark curve measurement was made and a "shaky" curve was obtained. A reverse dark curve measurement was made and a flat response curve resulted.

NOTE

Several interconnects were also noted to be in the early stages of work hardening.

5.9 Mead, Nebraska, Agricultural Test Station — October 1980

On 16 October 1980, with an ambient temperature of 68°F, a search for electrical failures was made at the Mead, Nebraska, test site. Twenty-six Block II Model C and four Block II Model D modules were found which had either reduced or zero short-circuit current.

A brief explanation of the conditions found in each type of module and the probable cause of failure is found in Paragraphs 5.9.1 and 5.9.2.

5.9.1 Model C Module Failure Analysis

When the 26 modules were flashed in the LAPSS, I-V curves were obtained, some of which were irregular in shape, showing the short-circuit current of 20 of the modules to be reduced to 26, 30, 32, (2) 36, (4) 38, 40, 44, 46, 48, 50, 52, (3) 56, 60, and 68 percent, respectively, of their normal values.

On four modules, no I-V curves could be obtained. Upon visual examination, one or more impact-cracked cells were found on each module which could cause the open-circuited condition.

On another module, an almost flat response I-V curve was obtained which showed the short-circuit current to be reduced to less than 1 percent of its normal value.

Visual examination showed the module to contain two impact-cracked cells, one of which could cause the cell string to open circuit. If this module were placed in the sun, it would become completely open circuited.

A normal I-V curve was obtained on the remaining module. When the module was visually examined, five cracked cells were found; one impact-cracked cell and four cells which had cracked, due to thermal mismatch, along the area of the cell which lays over a structural rib.

The module was placed in the sun to elevate the cell temperature. After approximately 15 minutes, the short-circuit current of the module was taken and found to be reduced to 60 percent of the normal operating current for this module.

Sixty-seven impact-cracked cells were found on the 26 modules, 24 of which could definitely cause an open circuit in a cell string. In addition,

16 cells were found which had cracked over a structural rib, none of which appeared to be able to cause an open-circuited condition but would cause some reduction in the operating current of the module.

NOTE

It's quite possible that the above modules have more impact-cracked cells with a potential to cause failure, than was noted. It has become increasingly more difficult, and sometimes impossible, to follow the more subtle radial cracks across the cells even though the microscope is used at 35X magnification and external high-intensity fiber-optic lights are used at varying angles. This problem is due to the worsening condition of the discoloration and/or staining of the anti-reflective coating on the cells.

5.9.2 Model D Module Failure Analysis

When one of the Model D modules was flashed in the LAPSS, an I-V curve was obtained showing the short-circuit current to be reduced to 92 percent.

When visually checked, one impact-cracked cell was found which could cause an open circuit in the cell string (Fig. 11). Also found was a pair of broken interconnects between two cells (Fig. 12).

To try to determine which condition was the actual cause of failure, a forward dark curve measurement was made and a normal curve was obtained. Using this curve as a monitor, heat was applied to the rear side of the module in the area of the interconnects between the two suspect cells.

Fig. 12. Block II Model D. Broken interconnects.

After approximately three minutes, the curve went flat, indicating that the interconnects had expanded and pulled apart; causing an open circuit in the cell string.

The fact that the cracked cell had not caused the module to fail was confirmed. Using a capacitive open

circuit tester the open circuit in the cell string was found to have occurred over the broken interconnects

Fig. 11. Block II Model D. Impact-cracked cell.

Fig. 13. Block II Model D. RTV split and blistered interconnects overheated.

and not over the cracked cell.

Two other modules were flashed, and highly irregular shaped I-V curves were obtained showing the short-circuit currents to be reduced to 15 and 20 percent, respectively, of the normal value.

The module, with the current reduced to 15 percent, was examined visually and four impact-cracked cells were found, three of which had the potential to cause an open circuit in the cell string. By one of the cells, a scorch mark was found on the substrate along the edge of the cracked area, indicating that the cell had become extremely hot. Due to the overheating of the cell, the RTV had blistered and split along the cracked area also. A similar scorch mark was found in this area on the rearside of the module, as well. A similar condition was found on the module that had the short-circuit current reduced to 20 percent.

A visual examination was made of the module and five impact-cracked cells were found, of which four could cause an open-circuited condition. One of the four cells had overheated, melting the solder on the interconnects, and leaving them free-floating, as well as causing the RTV to blister and split. A small chunk of RTV had fallen out also, leaving a hole down to the cell surface. Scorch marks were found along this area of the cell on the front and rearside of the substrate (Figs. 14, 15).

The remaining module was flashed and a flat response I-V curve was obtained, showing the module to have zero short-circuit current.

The module was examined visually and two impact-cracked cells were found,

neither of which appeared to be able to cause the failure. However, a pair of possible broken interconnects, between two cells were noted.

A forward dark curve measurement was made, but no curve was obtained until pressure was applied to the area over the suspect interconnects. As soon as the pressure was released, the curve disappeared. This verified that the interconnects between the two cells were completely broken and were the cause of failure in this module.

5.10 Natural Bridges National Monument — November 1980

On 12 November 1980, during a search for electrical failures at the Natural Bridges National Monument (NBNM) test site, three Model F Block III modules were found shorted to ground.

The three modules were flashed in the usual manner in the LAPSS, and a normal I-V curve was obtained for each module. Each of the modules was then flashed a second and third time with the leads connected alternately between the positive and negative terminals, and the metal case of the module.

With the leads attached between the negative terminal and the case, flat response curves were obtained for two of the modules. The third module produced an I-V curve indicating a short to the case through the negative side of the foil interconnect.

No I-V curves were obtained when the leads were connected between the positive terminal and the case of the first two modules. However, a curve was once again obtained on the third module, indicating a short to the case through the positive side of the foil interconnect as well.

Fig. 14. Block II Model D. Scorch mark on rear side of substrate.

The cover glass of one module was completely shattered (Fig. 15). When visually inspected, the module was found to have a burned area along one side, approximately $1 \times \frac{1}{4}$ inch, at the edge of the foil interconnect (Fig. 16). A small hole, caused by the arcing, was found in this area on the rear side of the module also (Fig. 17). Discoloration of the metal around the hole was found, indicating intense heating. This heating was assumed to be the cause of the shat-

tered cover glass as well.

The second module was found to have a burned area on the foil interconnect along the edge of a cell (Fig. 18). Long, blackened air bubbles were found which extended out from the burned area. The solder on the interconnects of this cell, as well as several other cells around the periphery of the module, appeared to have been overheated and the collectors on the cells were darkened. Two other small

Fig. 15. Block III Model F. Shattered cover glass. Arrow points to burnt area at edge of case.

burned areas were also found along the edge of the foil interconnect.

An area of discoloration with a small hole in the center, caused by arcing, was found on the rear side of the module in the area under a cell.

When the front side of the third module was examined visually, a cell appeared to have been overheated to a point where the solder on the interconnects had melted and then resolidified (Fig. 19). There was no evidence of shorting on the front of the module.

A hole was found on the rear (in an area under a cell) which measured

approximately $1\frac{1}{2}$ -inches long and 1-inch wide with an adjoining hole that measured approximately $\frac{1}{2}$ -inch long by 1-inch wide (Fig. 20).

The rear side plating of the cell was visible at the bottom of the hole. Burned and blackened RTV, a white residue, grayish ash, and bits of the foil interconnect were found in the holes. The foil interconnect appeared to have disintegrated in this area.

Small mounds of melted metal (probably part of the case) as well as a black sootlike residue were found around the periphery of the holes. The metal case around the hole was also discolored from the heat.

Fig. 16. Burned area (Fig. 15) where interconnect arced to case.

Fig. 17. Small hole on rear side of module caused by arcing.

Fig. 18. Burned area on foil interconnect by edge of cell.

Fig. 19. Overheated cell caused solder on interconnect to melt. Solder resolidified on cooling.

Fig. 20. Large hole on rear of case under cell. Arrow points to plating on rear of cell.

NOTE

The cause of failure found in all of the Block III Model F modules has been due to the foil interconnect shorting to the case. Since installation in January 1980, 31 modules have failed in this manner. This appears to be a manufacturer design problem, but this type of module is now no longer being manufactured. If failures continue at this rate, there will be no spares available for replacement.

6.0 LAPSS OPERATIONAL STATUS REPORT

At the MP&TL difficulties had been experienced in obtaining regular flash ignition from the LAPSS. Because the lamps had been flashed a total of 16,590 times (minimum life expectancy is 5,000 flashes) and were

long overdue to be changed, the xenon flash lamps were replaced on 27 January 1981.

By using a Block II Model C reference cell and a second corresponding reference cell, the uniformity of the beam was measured and aligned over a 6-by-6 foot target plane (Fig. 21). For a 6-foot-square area, when the center is set at 100 mw/cm², the corners are at 96 to 98 mw/cm². Once this target plane uniformity was established, the LAPSS was recalibrated by using the manufacturer's calibration procedure. This procedure is used to determine the zero offset and full-scale count values used by the computer to interpret test data.

Finally, the LAPSS was rechecked by flashing four standard modules. These modules had been previously flashed in 1978 and 1980. The values (Fig. 22) compare reasonably well on each

Fig. 21. LAPSS alignment.

Standard reference cell,
ST-24 (JPL)

Standard cell, Y-246
(NASA-LeRC)

1.00 = 100 mw/cm² @ 28°C

Fig. 22. Recheck of LAPSS on four standard modules after one and two years.

MODULE	DATE	Isc	Voc
SENSOR TECH BLOCK II LL No. 10014	6-13-78	.585	24.550
	6- 4-80	.585	24.650
	2- 2-81 *	.587	24.665
SENSOR TECH BLOCK II LL No. 10077	6-13-78	.570	24.925
	6- 4-80	.570	25.005
	2- 2-81 *	.576	25.065
SOLAREX BLOCK III LL No. 11926	7-25-78	1.407	23.295
	6- 4-80	1.399	23.750
	2- 2-81 *	1.412	23.840
SOLAREX BLOCK III LL No. 11927	7-25-78	1.376	23.780
	6- 4-80	1.378	24.000
	2- 2-81 *	1.395	24.115

* Flashed with new lamps

114880

flashing. Increases in short-circuit current (Isc) were between 0.4 and 1.4 percent.

7.0 MODULE DEGRADATION ANALYSIS—MOUNT WASHINGTON, N.H.

During the period of 28-30 January 1981, electrical and visual degradation analyses were performed on one Model D and two Model C block-III modules which had been removed from the Mount Washington Observatory test site in September 1979 after 12 months of exposure (Table 4). Also included here are the results of the analyses performed on one Block II Model B, one Block III Model E and two Block III Model F modules which were removed from the Mount Washington site in August 1980, after 11 months of exposure (Table 5).

It was found during the analysis of these modules that one of the Model F modules and the Model B module had become electrical failures.

Table 4

Model C and Model D Failure Analyses
Mount Washington Site
September 1978 to September 1979

Type of Module	Symptoms	Commentary
Model C	Electrical	The modules were flashed in the LAPSS and normal I-V curves were obtained for both modules. The first module (11560) had a short-circuit current of 4.95 amperes (a),

Table 4 (Continued)

Type of Module	Symptoms	Commentary
Model C		an open-circuit voltage of 24.43 v and a peak power of 9.07 w. The second module (11498) was found to have a short circuit of 4.93 a, an open-circuit voltage of 24.54 v and a peak power of 9.23 w.
		Forward and reverse dark curve measurements were made and normal curves were obtained for both modules. A voltage breakdown (hi-pot) test was performed on both modules, for one minute at 1500 volts, and the leakage currents were 0.40 and 0.27 μ a, respectively. All these electrical parameters show little or no degradation from normal.
	Tarnish	The use of tools on the interconnects, during the fabrication process, removes segments of the plating and exposes the copper base. These exposed areas tend to tarnish with time. This condition was found on the majority of the interconnects on both modules.
	Discoloration of AR coating	At receiving inspection, it was noted that numerous cells had irregular dark stains on the anti-reflective (AR) coating. These same stains, after field exposure, appear to be changing in color. They have now changed to various shades of rust on 30 cells of one module and 27 cells of the second module.
		Fading or lightening of the AR coating was also found on 28 cells of the two modules.
	Broken surface bubbles	Bubbles, which had broken at the surface, were found along the edge seal on the first module.
	Delamination	Specks of delamination were found in the terminal areas of the first module. In addition, a spot of delamination, found on a cell, measured approximately 1/16 of an inch in diameter.
	Corrosion	A residue of flux, which has turned green, was found on the buswires in the terminal areas of both modules.
	Protruding mesh	A strand of the nylon mesh that is used to isolate the rear sides of the cells from the substrate, was found to be protruding through the RTV at the corner of one module.
	Cracked cells	No cracked cells were found on the first module, however, the second module (11498) was found to have five cracked cells; one randomly cracked and four impact cracked. The random crack appeared to have started at a <u>surface chip</u> , which was located about

Table 4 (Continued)

Type of Module	Symptoms	Commentary
Model C		<p>one-third of the way into the side of the cell. The crack ran diagonally from the chip through one of the main collectors to the top edge of the cell where it exited to the left of the other main collector. This crack could only have happened during the assembly process as there was no evidence of the remnants of the silicon chip on the surface of the cell.</p> <p>The road maps for this module, from the JPL inspectors as well as the MIT LL inspectors, were checked and no indication of a crack or a scratch had been noted for this cell on either set of inspection records.</p> <p>The remaining four cells appeared to have been cracked by impact. Two areas of impact were found on one of the cells; one of which has the potential to cause an open circuit in the cell string. The cause of the impact cracks is unknown, but it is surmised to have been either hail or blowing debris.</p>
Model D	<p>Stained main collectors</p> <p>Broken surface bubbles</p> <p>Tarnish</p> <p>Collector dewetting</p> <p>Splits in the RTV</p> <p>Work-hardened interconnects</p> <p>Electrical</p>	<p>All of the 42 cells were found to have discoloration of the main collectors.</p> <p>Bubbles, which had broken at the surface, were found in several places along the edge of the module frame.</p> <p>Areas of bared copper found along the edge of the bus-bars and terminal strips were becoming tarnished. This condition was also found on one of the interconnects.</p> <p>One cell was found on which both collectors were dewetting from the silicon in the interconnect-to-collector contact area.</p> <p>A split in the RTV, 3/32 inch deep and 5/32 inch long, was found extending down to the surface of a cell.</p> <p>All of the 96 interconnects were categorized according to work-hardening as described in Paragraph 2.0. Sixty-two interconnects were found to have a granular appearance on the surface at stress points. The remaining 34 interconnects were found to have a granular appearance with a crease visible along the stressed area.</p> <p>Forward and reverse dark curve measurements were made and normal curves were obtained for both.</p> <p>When tested in the LAPSS, a curve was obtained showing the short-circuit current to be 1.16 a, the open-circuit voltage to be 23.09 v and a peak power of 18.25 w, which are normal values for this module.</p> <p>A voltage breakdown test was performed at 1500 v for one minute and no leakage current was detected.</p>

Table 5

Model B, Model F, and Model E Failure Analyses
 Mount Washington Site
 September 1979--August 1980

Type of Module	Symptoms	Commentary
Model B	Delamination	Areas of delamination ranging in size from 5/8 inch long and 5/32 inch wide to 5-5/8 inches in length and 1/2 inch in width, were found along the edge seal. Sand had seeped in under the RTV in some of these areas also.
	Splits in the RTV/hardcoat	Numerous splits, which had penetrated the hardcoat only, were found on the module surface. Splits, which had penetrated the hardcoat and the RTV and extended down to the surface of a cell or an underlying interconnect, were found in six places on the module. These splits ranged in length from 3/32 to 9/16 of an inch with a depth of approximately 1/16 to 3/32 of an inch.
	Corrosion	During the assembly process a residue of flux had been left on some of the interconnects due to improper cleaning methods. This residue has turned green on seven of the interconnects.
	Work-hardened Interconnects	Forty-three interconnects, including those between the terminals, were examined at high magnification for signs of work-hardening as described in Paragraph 2.0. Forty-two interconnects were found to have a granular appearance with a crease. The remaining interconnect, between cells 6 and 7, was found to be cracked.
	Electrical	The module was flashed in the LAPSS and no I-V curve could be obtained. Forward and reverse dark curve measurements were made and again, no curves could be obtained. Using the forward dark curve as a monitor, pressure was applied in the area over the cracked interconnect. A forward dark curve was momentarily obtained. The measurement was repeated for the reverse curve, and again, a momentary curve was obtained. Applying steady pressure in the suspect area, photos were taken of the forward and reverse dark curves. As soon as the pressure was released, the module, once again, became open circuited.

Table 5 (Continued)

Type of Module	Symptoms	Commentary
Model B		This module, a field failure because of the broken interconnect, will be shipped to JPL, along with a PFR, for further failure analysis.
Model F	RTV seepage	Both modules were found to have a slight seepage of RTV along the edges of the substrate on the rear side of the stainless steel case.
	Stains	Stains, previously noted on the cells at receiving inspection, have lightened on 16 cells of the two modules.
	Tarnish	Three cells of one module and four cells of the second module appeared to have main collectors and grid lines that were becoming tarnished.
	Darkening collectors	Forty-four cells on one module and 43 cells of the second module were found to have main collectors which had changed to differing shades of brown. The collectors of the cells located around the periphery of the module were a much darker shade of brown than those in the center of the module. Also, some of the darker collectors along the periphery had shades of green. Cause unknown.
	Foil interconnect	Darkened areas were noted on the edges of the foil interconnect on both modules, as well as along some of the interconnections on the cells. It appears that the Kapton tape covering the foil may be split in these areas, allowing moisture to seep in and cause the copper interconnecting foil to tarnish or discolor.
	Electrical	The modules were flashed in the LAPSS and normal I-V curves were obtained for both modules. The short-circuit current for the first module (12528) was 5.0 a, the open-circuit voltage was 7.0 v and the peak power was 26.36 w. On the second module (12529), the short-circuit current was 4.5 a, the open-circuit voltage was 7.0 v and the peak power was 24.32 w. Forward and reverse voltage breakdown tests were performed on both modules, for one minute at 1500 v. One module (12529) was found to have an acceptable leakage current of 0.23 μ a on both the forward and reverse tests.

Table 5 (Continued)

Type of Module	Symptoms	Commentary
Model F		<p>The other module (12528) was found to have a leakage current of $18.7 \mu\text{a}$, which is an unacceptable level according to the JPL Design and Test Specification for Block III modules. This module was initially tested by the manufacturer and a forward leakage current of $0.6 \mu\text{a}$ was recorded along with a reverse leakage current of $0.8 \mu\text{a}$.</p> <p>At receiving inspection at MIT LL, the forward and reverse leakage currents were noted to be $0.87 \mu\text{a}$ in both positions.</p> <p>This module was shipped to JPL, along with a PFR, for failure analysis.</p>
Model E	Stained collectors	<p>There was relatively little change found in this module. A light yellow staining was found on the grid lines of 36 of the 41 cells. On two other cells, the main collectors and grid lines had changed to a dark shade of yellow. Slight discoloration was found on the cell along the grid lines also.</p>
	Electrical	<p>Typically, the short-circuit current for this type of module is 1.4 a and the open-circuit voltage is 20.9 v. When flashed in the LAPSS, an I-V curve was obtained showing the short-circuit current to be 1.4 a, open-circuit voltage to be 24.0 v and the peak power to be 23.17 w.</p>

8.0 FIELD INSPECTION—FLORIDA SOLAR ENERGY CENTER AND THE UNIVERSITY OF TEXAS AT ARLINGTON

During the week of 17 February, members of the MP&TL visited the FSEC and UTA. An attempt was made to generate branch circuit and system level I-V curves at both sites.

8.1 FSEC

On Tuesday afternoon, the weather consisted of alternating periods of heavy clouds and heavy rain. On Wednesday, the cloud situation was not much better, and partial sun I-V curves were made to check shape and open-circuit voltage.

There are 12 branch circuits at FSEC, each containing 14 Block IV Model E intermediate modules in series. The modules are mounted on the roof on standoffs. These modules do not have a metal foil on the back side for humidity protection. There is only one bypass diode installed on each module.

Curves were generated using the MIT LL curve tracer at insolation levels between 45 and 85 mw/cm^2 . The ambient temperature was 24°C . The shape of each curve appeared normal,

with the range of open-circuit voltages between 267-271 v. This spread was due more to varying insolation than any problems in the array. An example of a branch circuit I-V curve at 85.1 mw/cm² is shown in Fig. 23. Figure 24 shows the array I-V curve at 50.5 mw/cm².

The site manager reported that about one-third of the Model E modules received contained one or more cracked cells. Many of these cracks were evident by visual inspection on the roof because the cracks are highlighted by discoloration. In addition, over one-half of the modules have discolored collector lines similar to those observed at NBNM. The discoloration is caused either by solder flux materials (such as chlorine) or by moisture penetration, or by a combination of these factors. In the near term, the discoloration causes little or no measurable electrical degradation, but the long-term effects are unknown.

System and branch circuit measurements are easily made from a control panel in the garage. It was recommended that the control panel cover be locked.

JPL representatives made cell hot-spot measurements with an infrared camera. The inclement weather hindered them also, but measurements revealed several "hot" cells. The hot cells were operating 5° to 6°C hotter than their neighbors, and in one case a hot spot coincided with a cracked cell.

8.2 UTA

The weather at the UTA field site was much better than at FSEC being sunny and cloudless. The UTA site now consists of 16 branch circuits containing Block III Model C modules. These modules are silicon rubber encapsulated with heavy aluminum substrates. Electrically, each branch circuit consists of four modules in parallel by ten in series, with a bypass diode installed on each group of four.

Fig. 23. FSEC branch circuit. 15 Block IV Model E intermediate modules in series.

Fig. 24. FSEC array I-V curve.

Initial I-V curves were made for each branch circuit prior to cleaning. The array was washed and subsequent I-V curves were also generated. System level curves were also generated before and after washing; these curves, recorded on tape, are on file at the MP&TL.

Figures 25 and 26 represent system level I-V curves before and after washing. Normalized to 100 mw/cm² insolation, the power output before washing was 5180 w and after washing was 5778 w, for a net improvement of 598 w. The array was first cleaned in April 1980 at the time of installation. Further data for each branch circuit is presented in Table 6. The power loss between April and February ranged between 5.5 and 11.7 percent.

In generating the branch circuit level I-V curves, it was noticed that a step occurred near the peak power point for circuit 8 (Fig. 27). After the failed module was located, removed, and replaced, a new I-V curve was gen-

erated (Fig. 28). This is the seventh failure (of 640) since April 1980. The module has been sent to the MP&TL for analysis.

Leakage-to-ground measurements were made for both the positive and negative sides of each branch circuit. Leakage currents ranged between 1 and 4 μ a, which are similar to the acceptable values recorded at the Mead, Nebraska, site on an earlier version of the same module.

Fig. 25. UTA system level curve—dirty.

Fig. 26. UTA system level curve—clean.

Table 6

Soil Accumulation Data at UTA
 April 1980–February 1981
 (Module-Type Block III Model C)
 (Encapsulation Silicone Rubber)

Branch Circuit	Power Before Cleaning*	Power After Cleaning*	Percent Loss Due to Dirt
1	337.6	382.2	11.67
2	328.5	375.0	11.69
3	338.1	368.6	8.27
4	336.3	364.6	7.76
5	331.5	368.6	10.06
6	326.4	360.8	9.53
7	350.2	370.3	10.83
8	332.3	358.4	7.28
9	339.5	362.3	6.29
10	342.0	362.0	5.52
11	332.9	356.4	6.59
12	342.0	360.4	5.10
13	336.4	359.0	6.30
14	338.5	372.6	9.15
15	338.5	358.4	5.55
16	340.3	365.8	6.97
Array	5180.0	5778.3	10.35

* Normalized to 100 mw/cm²

Fig. 27. UTA circuit 8 with failed module.

Fig. 28. UTA circuit 8 after failure replacement.

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